Failure Analysis of a Rockslide on Sunset Ridge Fire Access Road San Gabriel Mountains, California

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Contents

Abstract:

During this project, I studied a road cut along the Sunset Ridge fire access road in the San Gabriel Mountains, CA. This road failed during the early 1990s during a period of heavy rainfall. Debris that blocked the road for several years has been excavated, exposing a NE-facing triangular scar in fractured crystalline rock. The present-day slide scar is 30 meters high at its apex, and widens to 36 meters at road level. The objectives of this project were to reconstruct the pre-slide geometry and to determine the structural and mechanical conditions that lead to the failure.

Fracture analysis entailed systematic mapping of foliation, joints, and faults along accessible reaches of the slide area. Gently NW-dipping foliation striking into the slope face was not a major factor in the failure. Two intersecting sets of NE-dipping joints and faults played important roles in activating the slide block, originally rhombus-shaped in cross section. A steeper set coincides with a prominent fault (N36W/64-80NE) that bounded the rear of the block and facilitated its release. A shallower set (N30W/25-45NE) represents adversely dipping planes that projected out of the original road cut. A corresponding basal slide surface (N40W/28NE) is exposed 5 meters above the road level. The SE edge of the slide bock was released along a steep cross fault (N20E/75SE). Thickness of the block tapered from 4 meters on the SE side to zero at the bounding ridgeline on the NW side.

The slide area was surveyed with a Trimble Total Station, and ArcGIS was used to create a topographic map with a 2 foot contour interval. Fracture orientations were then plotted on this base map. The volume of the slide block was determined by subtracting topography of the existing slide scar from a projected surface representing the original slope and road cut. Assuming shear failure along the basal slide plane, stability equations were set up to determine combinations of cohesion and friction angle needed for failure (safety factor = 1). Calculations for friction angles yield values between 10 and 30 degrees for geologically reasonable cohesion and water conditions.

Introduction:

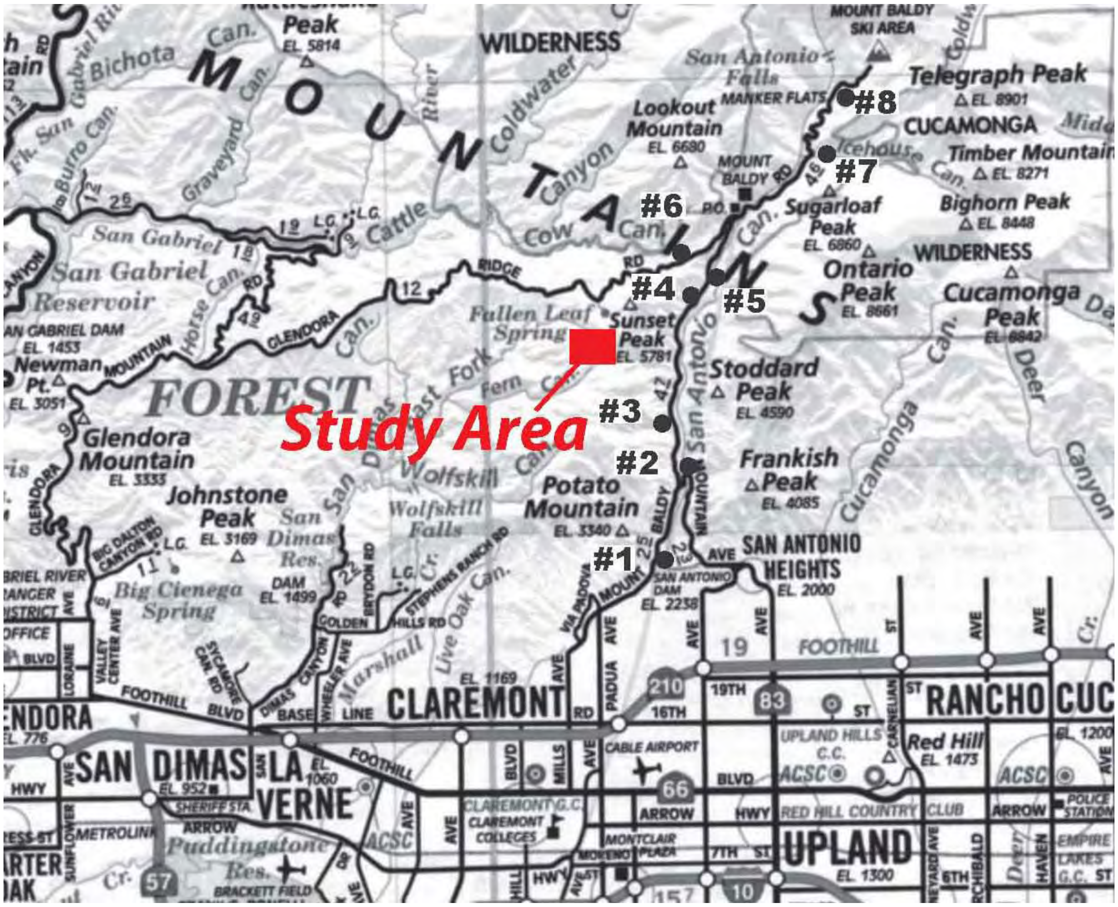

Figure 1. Area map with field study area highlighted.

The purpose of this project was to study and determine factors that caused a landslide on the fire access road just off Sunset Ridge Road in the San Gabriel Mountains of Southern California. The landslide occurred in the early 1990's and covered the access road into the Experimental forest. The road has since been cleared and reconstructed. Another objective was to find out if the slide happened due to the massive amounts of rain that occurred in those years, or if it had something to do with the road cut itself. These objectives were accomplished by taking field measurements of the landslide scarp, fractures, foliations, and faults with both compasses and surveying equipment such as the Trimble Total Station. ArcGIS maps were generated, the data was plotted on stereonets to determine general plane relations, and mathematical equations were applied to establish landslide controls such as friction angles and cohesion. Results from this study can be used to help reduce similar landslide occurrences in the future by understanding the controlling factors and applying them to the engineering and construction of future road cuts.

The location of the landslide is on a fire access road off Sunset Ridge Road, which hugs to the northern facing slopes and ridges of the San Gabriel Mountains, just west of San Antonio Canyon. There are numerous and spectacular landslides throughout the San Gabriel Mountains, but the most extravagant and easily accessible are the landslides in and around San Antonio Canyon. Some of the Paleoslides include: Sunset Peak Slide, and Hog Back Slide (Hibner, Herber, Rogers, 1991). Sunset Peak slide is located west of San Antonio Creek and just south west of Hog Back slide which crosses San Antonio Creek. Sunset Peak Slide generated a volume of about 9 million cubic yards. Hog Back only generated about 5.5 million cubic yards (Herber, 1987). Both these slides were back-analyzed and were found to have had toe undercutting and adversely dipping fracture sets which ultimately lead to failure.

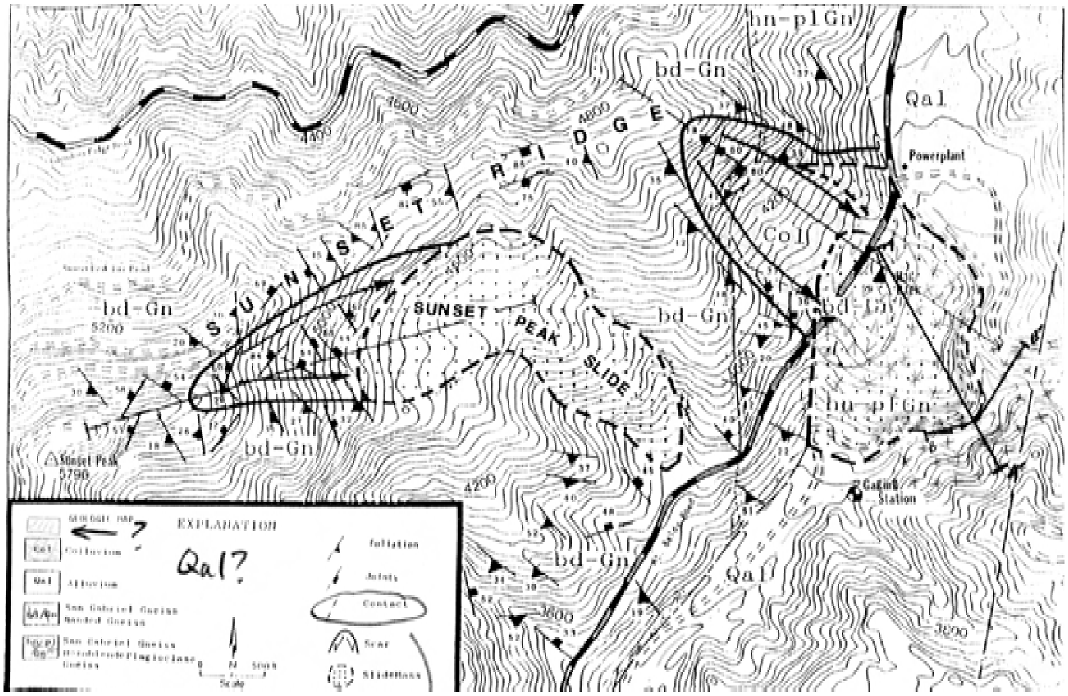

Figure 2. Hog Back and Sunset Peak slides outlined in a zoomed in topographic map. (Rogers,Herber, Hibner, 1991)

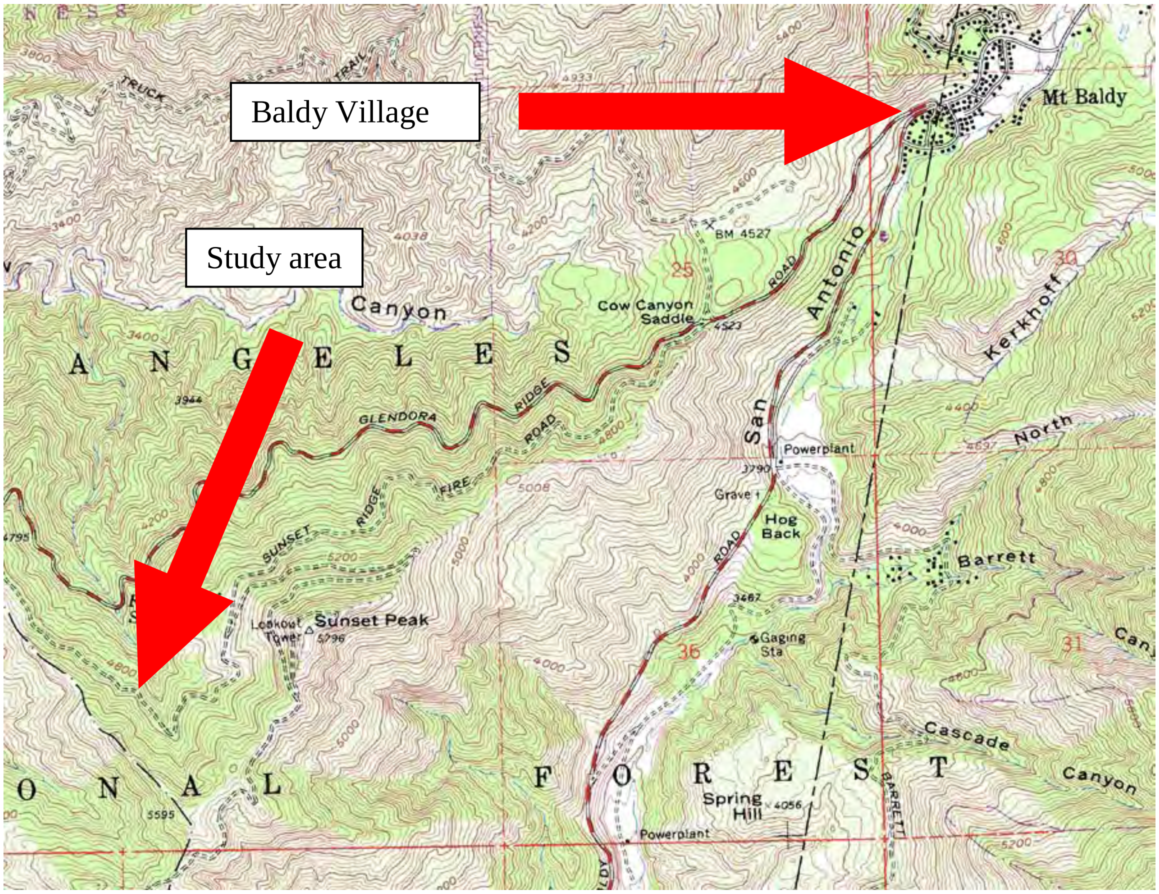

Figure 3. US Topographic map of study area. Arrows showing exact study area and reference to Baldy Village

The access road lies within the vicinity of the Sunset Ridge Fault Zone (Nourse, 2002). The presence of this fault zone coincides with incredibly fractured bedrock at the landslide location.

Some of the faults seen in the landslide area, exhibit epidote slickensides. The San Gabriel Mountains are composed largely of intrusive igneous and metamorphic rocks as shown on the geologic map section 1700000 San Bernardino Geologic Quadrangle (Morton et al. 2003). The landslide material at the project location area consists mainly of foliated granodiorite, patches of augen gneiss, and a few cross-cutting basaltic dikes.

II. Data:

IIa. Field Work:

Figure 4. Surveying using the Trimble Total Station on the fire access road directly beneath the landslide scarp.

Data collection was accomplished by taking field measurements with both Brunton compasses and surveying equipment (Trimble Total Station). The Trimble Total Station is an optical surveying instrument that has a theodolite, electronic distance meter, and GPS which can be used to measure distances to a certain point. To operate this Total Station, one person would go up the desired coordinate location with a reflective marker at the top of a staff, of which the length is known. This length is entered into the Station along with the Station's height to land surface (measured from the base of the Station to the ground). The operator then aligns the cross-hairs of the Station with the marker (Figures 4 and 5).

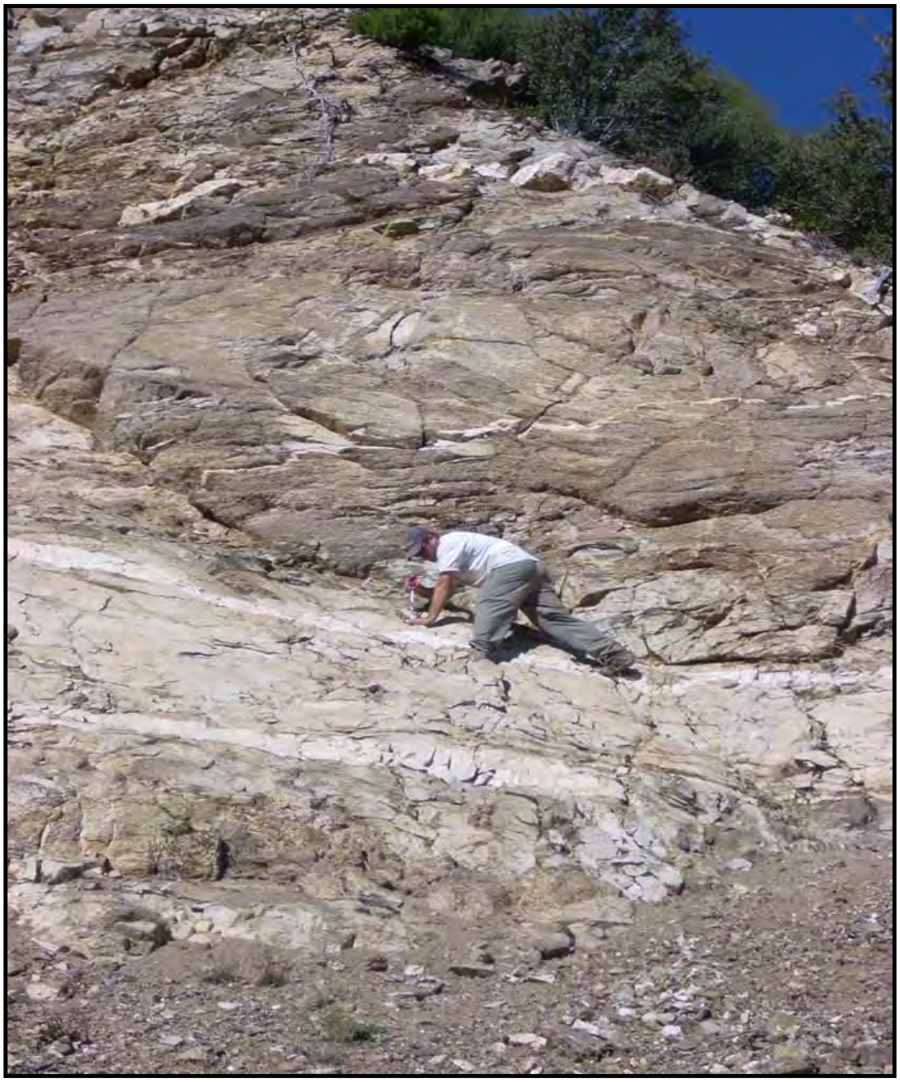

Figure 5. Using the surveying prism to mark the daylighting fracture which is oriented sub-parallel to the lower slide surface.

The station emits a laser and is able to determine the position of the point in space from the reflection received from the marker. This position is given in the form of x, y, and z coordinates. Bunton compasses were then used to measure the strike and dip of various structural features corresponding to surveyed points (Figures 6 and 7).

Figure 6. Taking strike and dip of a set of fractures oriented with the steep back release surface.

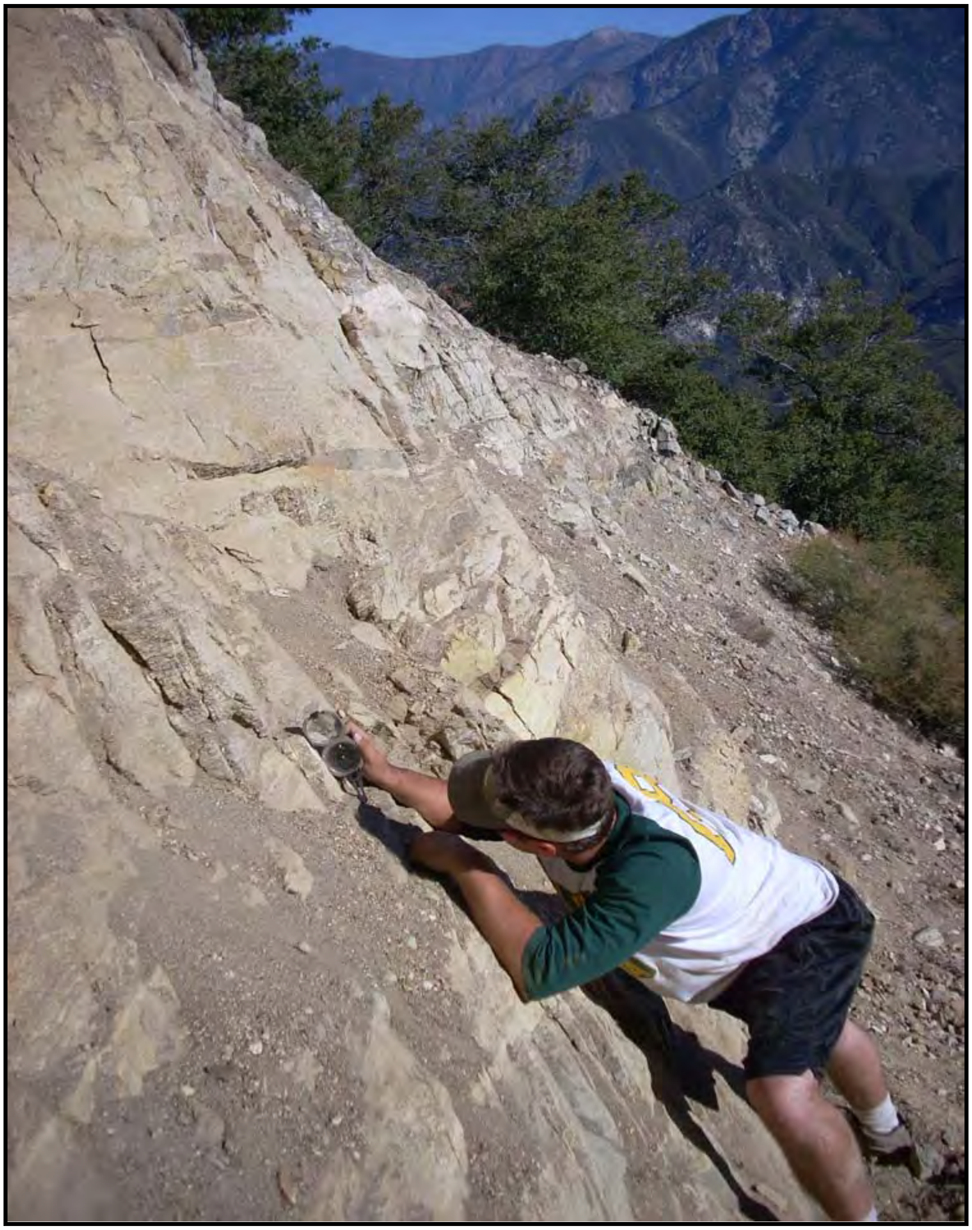

Figure 7. Measuring the steep dip of the back release surface. This is looking towards the North West.

IIb. Data Reduction and Map Presentation:

The features measured were foliation of the bedrock, fractures or joints, and faults. All sturctual measurements as well as the x, y, z survey coordinates from the Trimble Total Station were then input into ArcMap, the mapping feature of ArcGIS. Way points were plotted precisely and elevations contoured using 3-D analysis tools

(IDW, interpolation, and contour). Thus, a more detailed topographic map of the landslide area was generated with a contour interval of 2 feet (Figure 8).

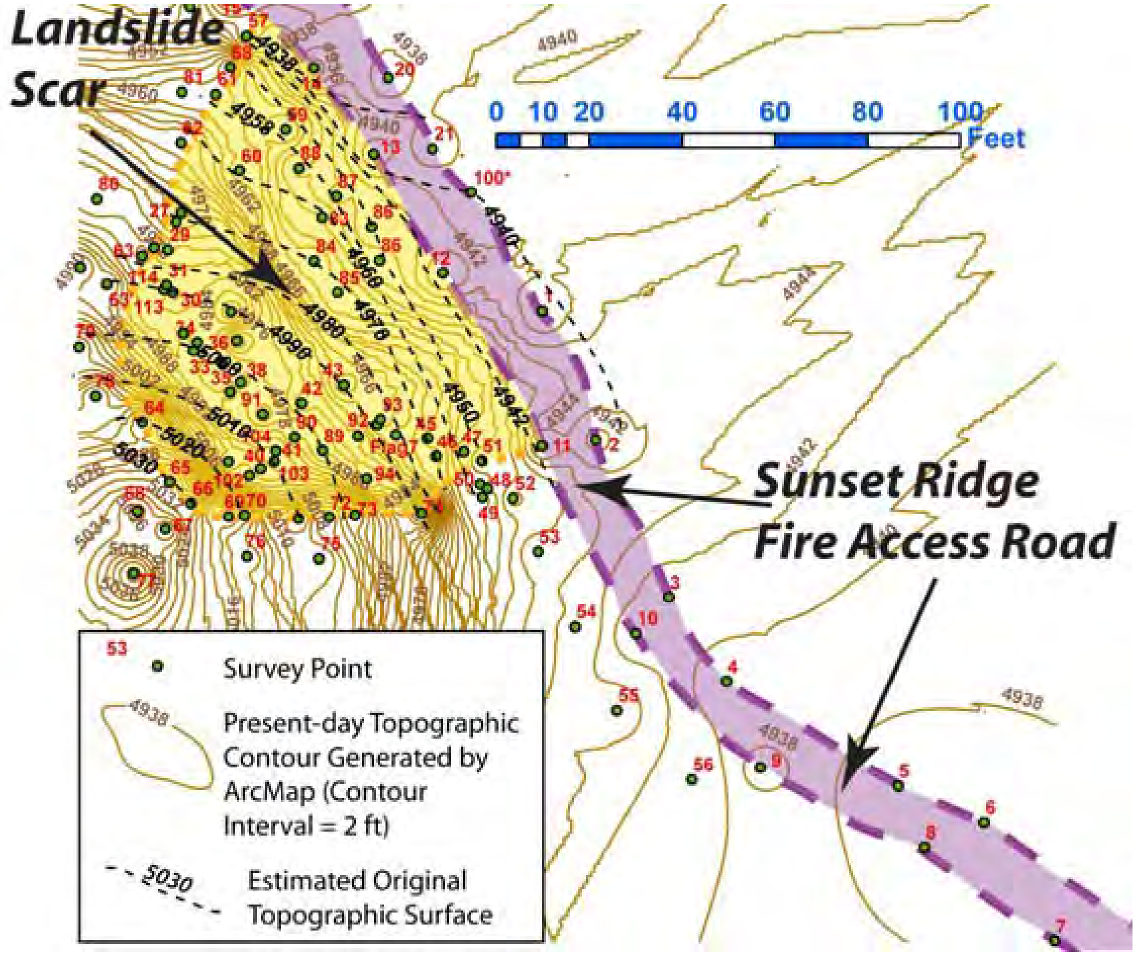

Figure 8. The survey map, showing topographic details of the slide scar and the estimated pre-slide topography.

Structural data was also plotted onto a pre-existing USGS topographic map precisely at known waypoints using symbology tools. Structural points were touched up in Adobe Illustrator to show the location of the various landslide scarp and road features. The structural points were overlain on the contour map to produce composite maps of the area for different features (Figures 9 and 10).

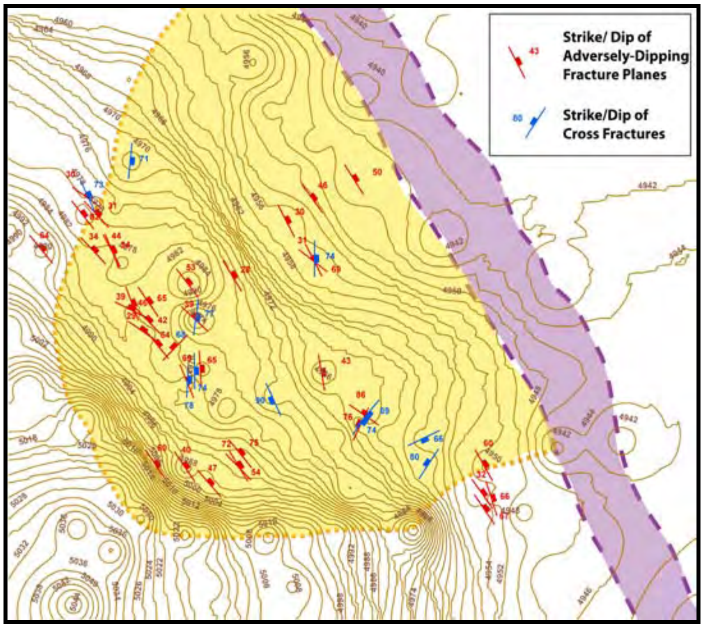

Figure 9. Fractures (joint) data plotted against an ArcMap topographic base layer.

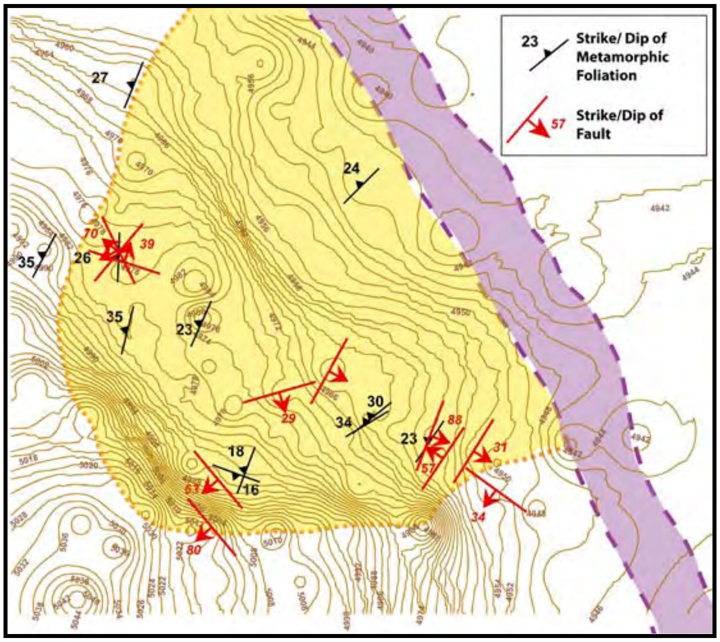

Figure 10. The Foliation and Fault data collected plotted against the ArcMap topographic base layer.

Strike and dip orientations of structural features (foliation, fractures, and faults) were measured in the field and marked with a GPS waypoint. The measurements were plotted on stereonets using the StereoWin plotting program by Richard Allmendinger.

IIc. Stereo Plots:

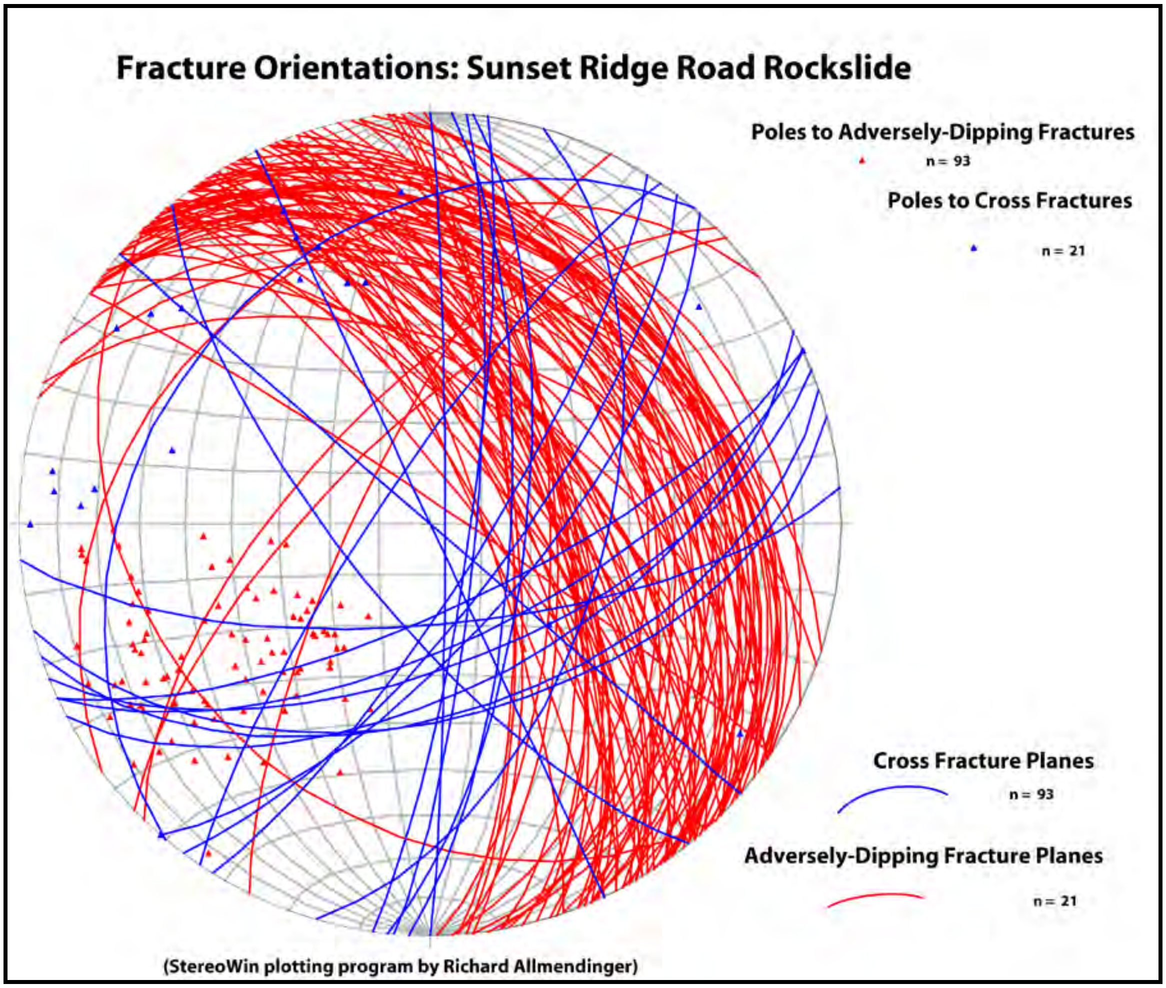

Figure 11. The fractures or joints fall into two groups: North east striking with steep dips, and North West striking with moderate to steep North East dips.

Different plots were made for fracture orientation (Figure 11), fault orientations (Figure 12), and metamorphic foliation (Figure 13). Using these plots, it is possible to see the general trend of these planar features and their typical orientations.

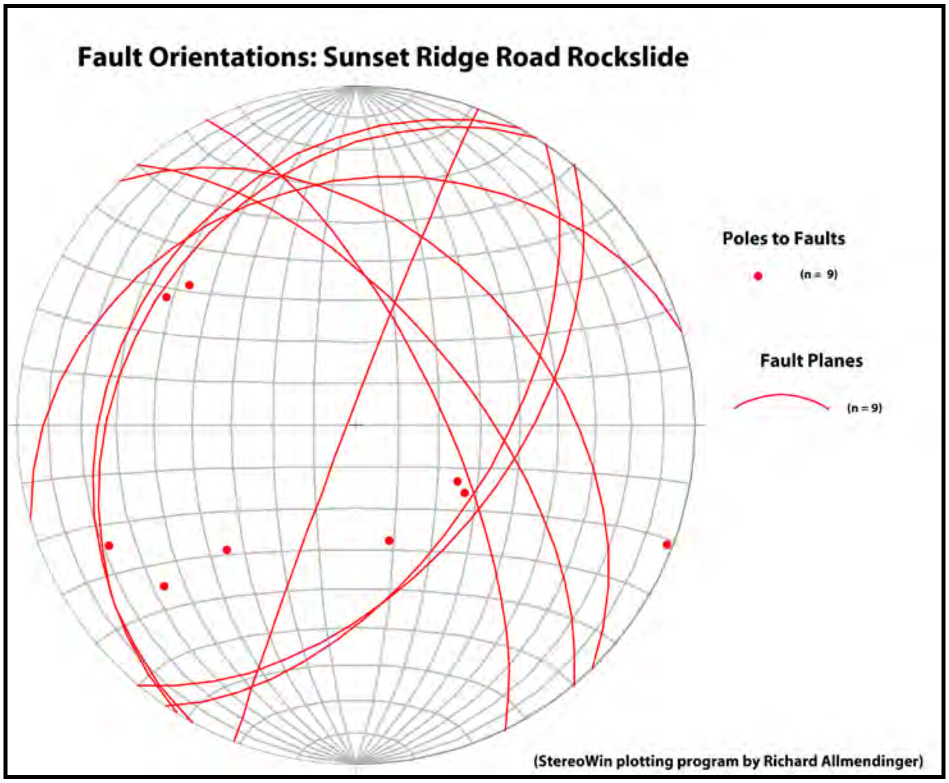

Figure 12. Stereonet with the fault planes dipping North West, North East and South East.

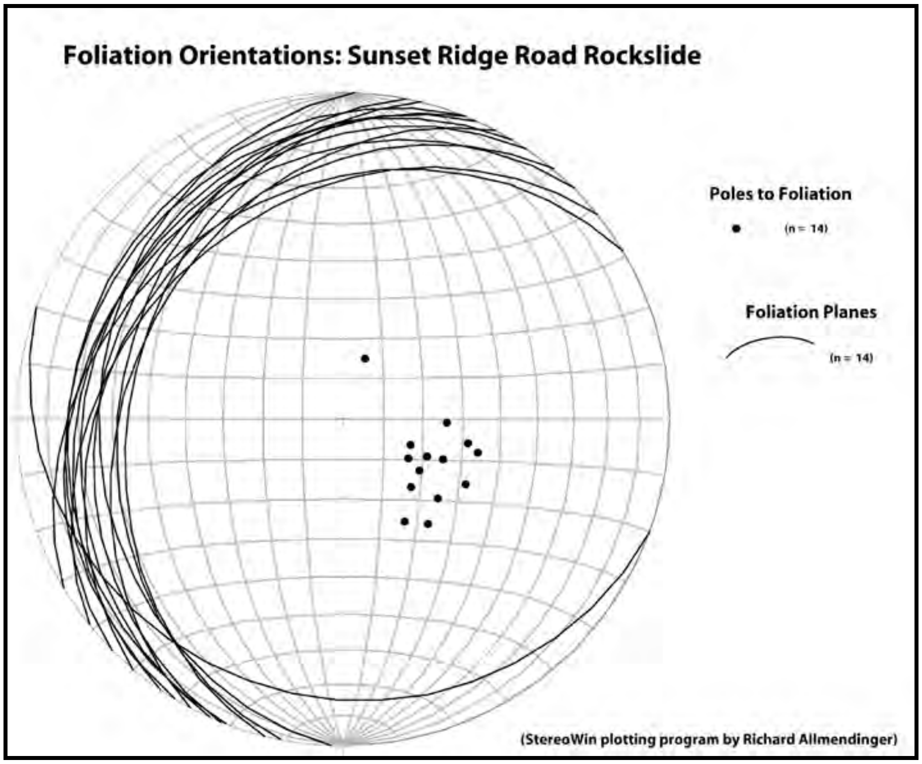

Figure 13. This stereonet is showing the metamorphic foliation dipping shallowly to the North West.

Fault planes in the landslide area do not plot in one specific orientation but consist of faults that dip to the NW, NE, and SE with dips generally between 50 and 70 degrees. Foliation orientations in the metamorphosed granodiorite plot consistently with a NE trend and NW dip of about 30 to 40 degrees. Fracture joint sets fall into two primary groups: those that strike to the NE with a steep dip to the SE, and those that strike to the NW with a moderate dip to the NE. The fractures that dip to the SE represent cross fracture planes that lie oblique to the day-lighting trend of the majority of the fractures.

Most of the fractures dip to the NE and are referred to as adversely-dipping fracture planes. The adversely-dipping fracture planes themselves from two dip populations, (Figure 14).

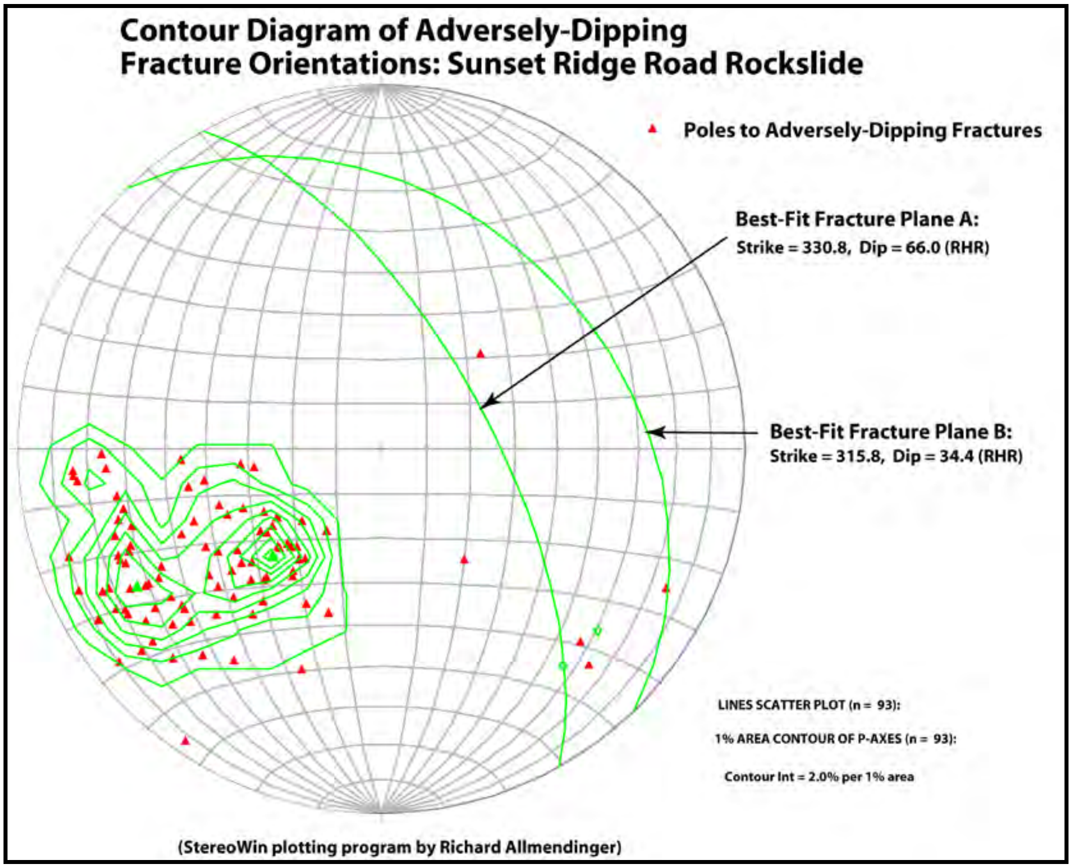

Figure 14 Adversly NE-dipping fractures from two dip populations. The shallower set corresponds to the basal slide plane, while the steep set marks the rear surface of the slide mass.

In Figure 14, the poles of the adversely-dipping fractures were plotted and best fit strike and dip planes were found for these two dip populations. The shallower set corresponds to the basal slide plane, while the steep set is generally parallel to the rear release surface of the slide mass. The best fit orientation of the shallow set is sub-parallel to the basal slide plane that was measured in the field (Figure 15), and used in the force diagram model and calculations for analysis.

Figure 15. The basal slide plane is shown in the cleared section or slide and is roughly parallel to the shovel head.

IIIa. Slide Block Geometry

The contour map generated in ArcGIS was used to create cross sections of the landslide for total volume calculations. The landslide area was split into 5 sections, through which the profiles were drawn (Figure 16). The existing face was drawn in profile from the waypoints collected in the field.

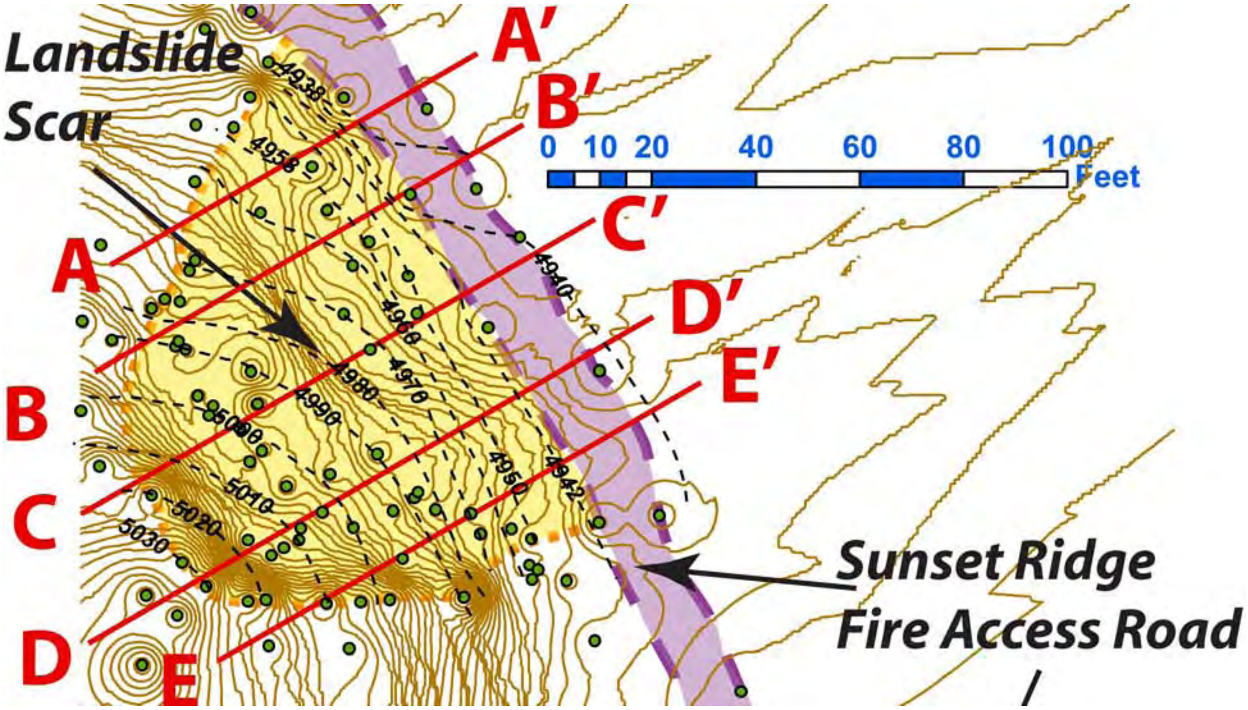

Figure 16. Topographic ArcMap with its survey points and hypothetical pre-slide topography. It also shows locations cross-sections.

Then the pre-landslide hill surface was reconstructed by extrapolating from the waypoints taken on edges of landslide (redlines in profiles, Figure 17). The landslide area for each section is therefore represented by the area between the extrapolated surface and the existing surface. This area was calculated by counting the squares of the representative area on the cross section (each small square is equal to 4 square feet).

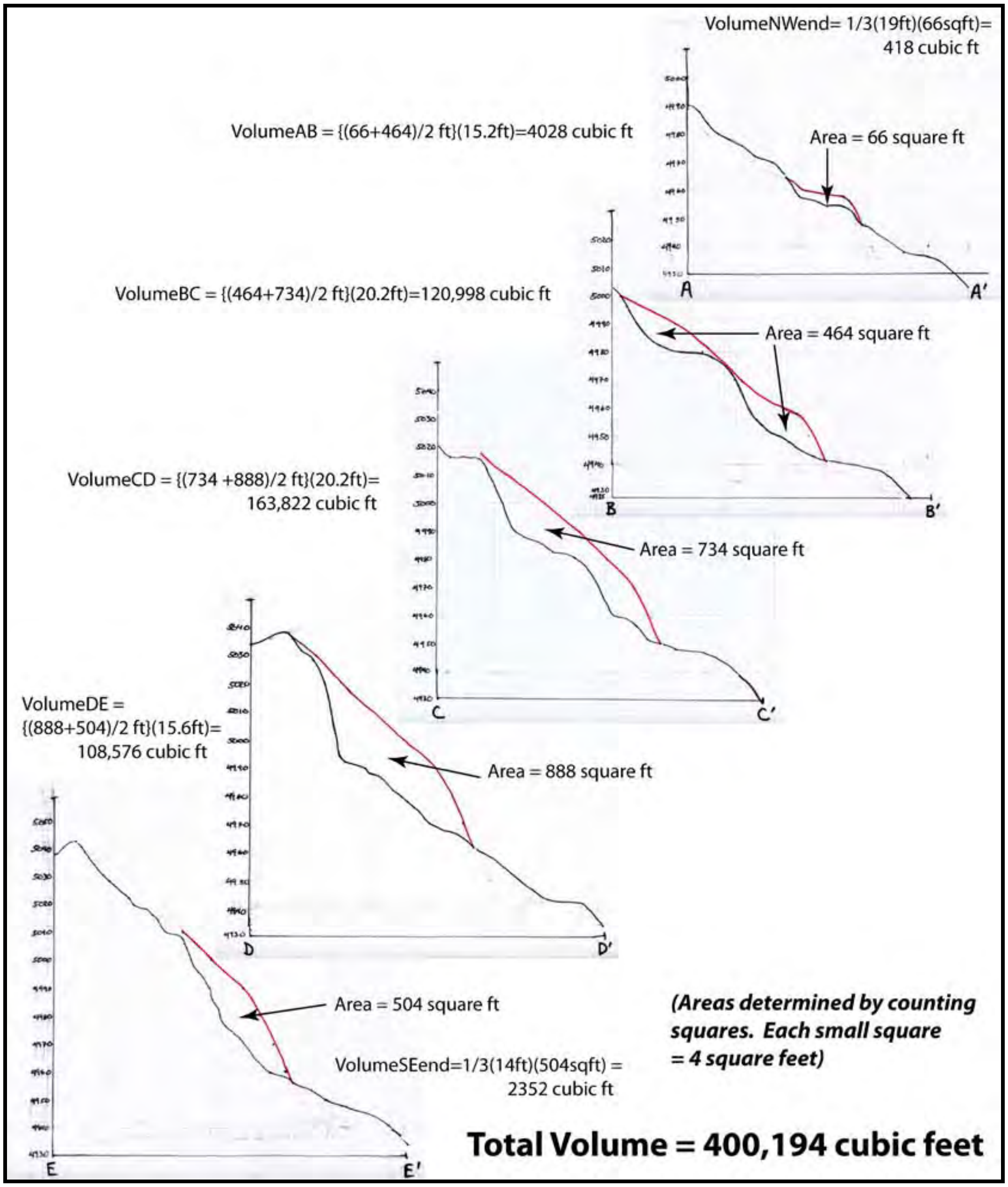

Figure 17. Drawn out profiles and calculations of the five cross-sections in figure 16

The areas on either side of consecutive cross sectional lines are averaged and then multiplied by the distance between them. This results in a volume for that “slice” of the landslide. For example, the landslide area from A-A’ is 66 ft^2 and the area from B-B’ is 464 ft^2. By taking the average of these two values results in an average area of 265 ft^2. This average area is then multiplied by the distance between the two cross sectional lines (15.2 ft), resulting in a slice volume of 4028 ft^3. The total landslide volume was then calculated by adding the four slices together as well as the volume estimated on the edges of the landslide. This total volume was found to be about 400,194 ft^3. Multiplying this volume by a unit weight of 160 lbs/ft^3 (a representative weight for crystalline rock) gives an estimated value of the landslide material dry weight of 64,031,040 lbs.

The slide mass was modeled as an irregular shaped block on an inclined slide plane with a dip of 28° (Figure 18).

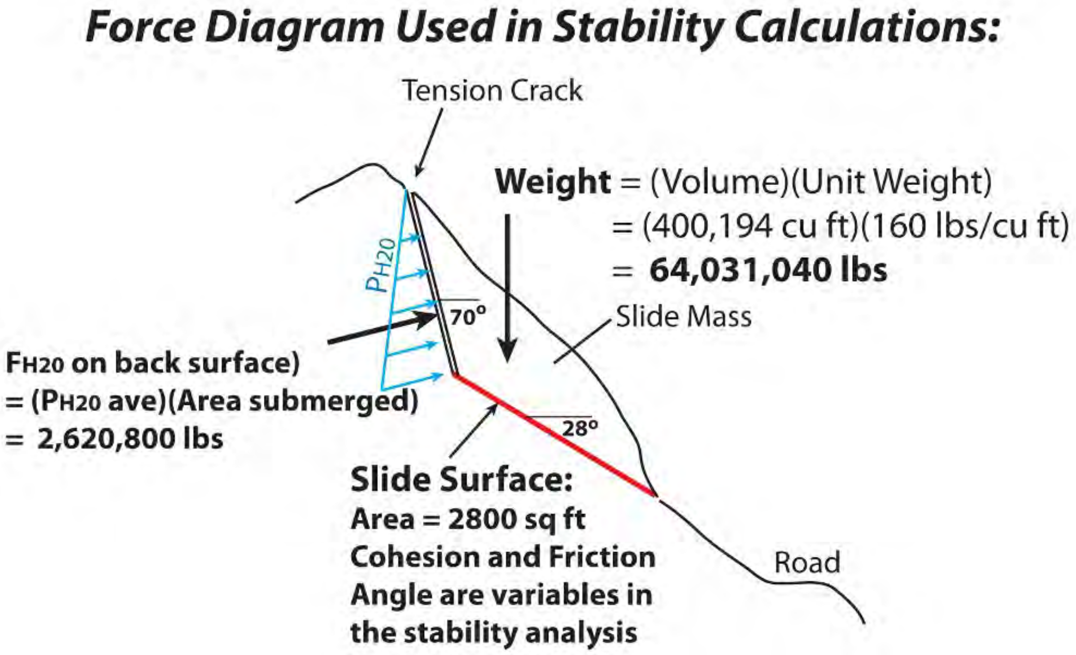

Figure 18. This force diagram shows important parameters considered in this analysis.

This dip represents an average of about 5 fracture orientations where we dug to get to the basal plane. The block was released at the rear along a tension crack with zero cohesion. Safety factor equations for various combinations of friction angle and cohesion were solved for assuming the safety factor is equal to one. Both dry and wet conditions (with the tension crack filled with water) were considered.

The stability equation representing dry conditions is given by the following equation:

$$SF = \frac{C+\tan\Phi\,[W\cos(28)/A]}{W\sin(28)/A}$$

Where SF is the safety factor, C is the cohesion, Φ is the angle of internal friction, W is the weight of the slide block, and A is the area of the basal slide surface. A was solved for by averaging the length of the slide surface in cross sections A-A' through E-E', then multiplying by the map distance between the sections. This is taken to be 2,800 ft^2. Setting the SF equal to 1.0 (failure condition), various combinations of C and Φ were solved for. The results from these calculations were then plotted on a graph in the form of a line (figure 19).

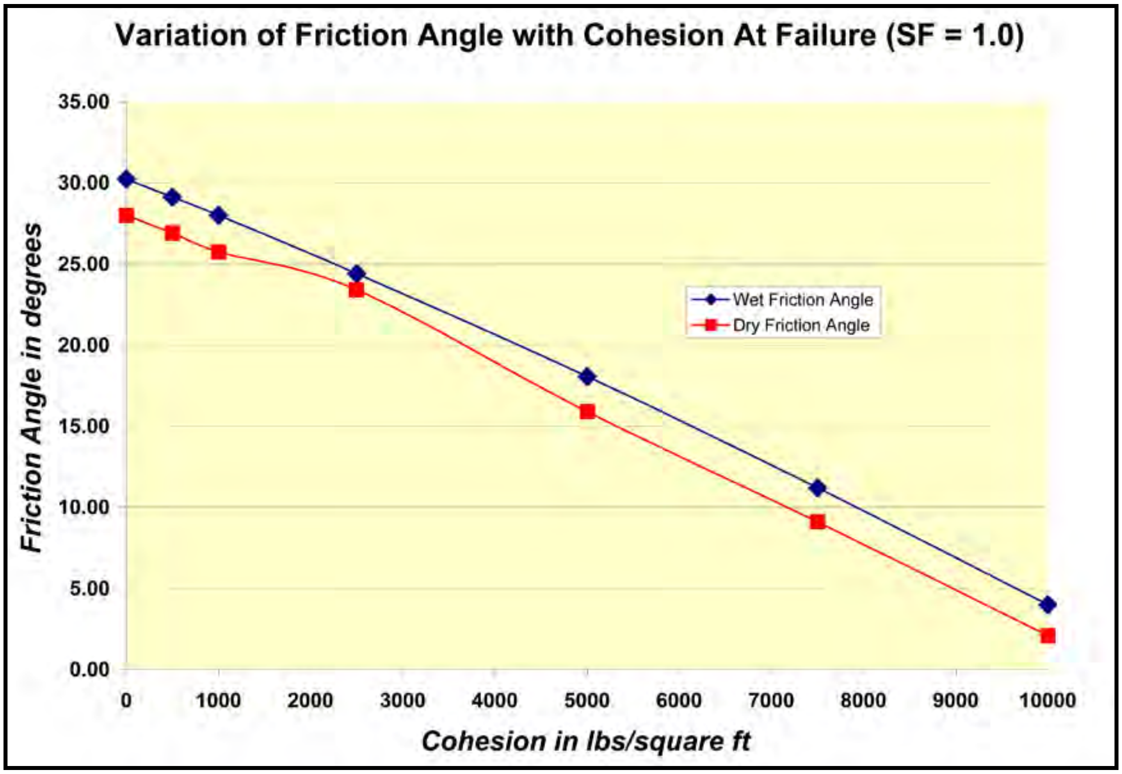

Figure 19. This Graph illustrates the difference between wet and dry conditions concerning friction angle and cohesion.

A similar stability equation was used to calculate Φ for varying values of C under wet conditions. This equation is given as:

$$SF= \frac{C+\tan\Phi \{[W\cos(28)-F_{H2O} \sin(48)]/A\}}{[W\sin(28)+F_{H2O} \cos(48)]/A}$$

Where F_{H2O} is the resolved force of the water on the back of the tension crack, at 48° (this 48° is the value of the angle between the direction of FF_{H2O} and the slide plane. The force of the water is equal to the average water pressure on the back of the block multiplied by the submerged area. This value works out to be about 2,620,800 lbs. Again, multiple values for C were chosen and Φ was then solved for from the equation when SF is set at 1. These results are also shown in Figure 19. Both the wet and dry condition lines are similar (as cohesion increases, the friction angle decreases), but the wet friction angle has higher friction angle values than the dry for the same cohesion value. This makes sense because one would expect more friction to hold the block in place with and extra water force.

IV. Conclusions/Recommendations:

A stability analysis was carried out on a landslide scar off Sunset Ridge Road for hypothetical dry and wet conditions. By setting the safety factor equation equal to 1.0, it is possible to back-calculate geologically reasonable combinations of cohesion and friction angle for various scenarios. The Sunset Ridge road cut failed because of adversely-dipping fracture plane geometries. The slide mass failed along a moderately NE-dipping basal slide plane that day-lighted out of the original road cut. Steeply NE-dipping fractures facilitated release of the slide mass at the rear. The failure model that perhaps best fits the conditions of failure would be a wet case scenario in which the tension crack is filled with water. This is due not only to the failure probably occurring after periods of heavy rain, but also because the fractures would normally have some amount of water in them in normal conditions. The effects of this added water is not only extra pressure exerted on the back surface of the slide mass (at the tension crack) but also the likely reduced friction angle on the basal slide surface assuming that some clay was present. Water within the slide mass itself would make it heavier and cause a subsequent driving force downhill. All of these factors make it easier for a section to fail under wet conditions than under dry ones.

This project has shown how helpful modern surveying equipment and ArcGIS tools are in helping analyze rock failure and other geological engineering applications.

Through the creation of a detailed topographic map and field measurements, landslide parameters such as volume, weight, and block orientation were able to be fairly well estimated to the point that they could be used in stability equations. Worst case scenarios would be under wet conditions, and would provide valuable parameters for risk assessments. Analyzing failed slopes can lead to insight on how to better engineer and construct road cuts in the future.

V. Acknowledgments:

I would like to thank Mike Oxford of the United States Forest Service for providing access to this part of the San Dimas Experimental Forest, Francelina Neto of Cal Poly Pomona's Civil Engineering Department which generously loaned me the Total Station, and the computer facilities, software such as Adobe Illustrator, and field vehicle provided by the Geological Sciences Department., also the Geography Department who provided the Arc GIS software and Richard Almendinger. I would also like to give a special thanks to my advisor, Dr. Jon Nourse, who helped tremendously with the field work, map generation, and calculations that were an integral part of this project, and whose advice and guidance got me through it.

Works Cited:

Rogers, J. David (Rogers/Pacific, Pleasant Hill, CA, United States); Herber, Lawrence J.;Hibner, Thomas H. 1992, Paleolandslides in San Antonio Canyon, eastern San Gabriel Mountains, California. Association of Engineering Geologists, 1992, Vol. 4, pp. 579-594 Association of Engineering Geologists : Sudbury, MA, United States

Herber, Lawrence J. (California State Polytechnic University, Department of Geological Sciences, Pomona, CA, United States); Hibner, Thomas H.; Ressel, Michael W., Jr.; Vrabel, Craig; Rogers, J. David ., 1991, Failure mechanisms of catastrophic subalpine paleolandslides in crystalline rok of the central San Gabriel Mountains; San Antonio Canyon, Southern California. Geological Society of America, 1991, Vol. 23, Issue 5, pp. 126-127Geological Society of America (GSA) : Boulder, CO, United States
United States

Morton M. Douglas, Minnich A. Richard, Sadler M. Peter, 1987, A Field Guide to Landslides in the Inland Valleys and Adjacent Mountains of Southern California. The Inland Geological Society. University of California Riverside: Vol 2 p. 20 – 31.